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Review

Strategic plant choices can alleviate climate change impacts: A review

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ABSTRACT

Ecosystem-based adaptation (EbA) uses biodiversity and ecosystem services to reduce climate change impacts to local communities. Because plants can alleviate the abiotic and biotic stresses of climate change, purposeful plant choices could improve adaptation. However, there has been no systematic review of how plants can be applied to alleviate effects of climate change. Here we describe how plants can modify climate change effects by altering biological and physical processes. Plant effects range from increasing soil stabilization to reducing the impact of flooding and storm surges. Given the global scale of plant-related activities such as farming, landscaping, forestry, conservation, and restoration, plants can be selected strategically—i.e., planting and maintaining particular species with desired impacts—to simultaneously restore degraded ecosystems, conserve ecosystem function, and help alleviate effects of climate change. Plants are a tool for EbA that should be more broadly and strategically utilized.

1. Overview of the problem

Global climate change threatens the functioning of weather patterns, ecosystems, societies, and economies (Grimm et al., 2013; Staudinger et al., 2013). *Climate adaptation*, "the process of adjustment to actual or expected climate and its effects" (Pachauri et al., 2014), is largely designed to lessen the negative impacts of climate change on recipient natural and human systems (Halofsky et al., 2015; Lesnikowski et al., 2015; Stein et al., 2013). Ecosystem-based Adaptation (EbA) is a specific type of climate adaptation that "uses the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change" (Gosnell and Vasseur, 2017). There is a rich literature describing how plants, as *ecosystem engineers*, alter microenvironments and drive ecosystem processes (Mullan Crain and Bertness, 2006), and the ecosystem engineering properties of plants are part of the toolbox for EbA. Examples of EbA include upland reforestation to ensure continued drinking water supplies and reduce flooding, bolstering agrobiodiversity to increase food security, and creating marine protected areas to reduce ocean-based income losses (Andrade et al., 2011; Chong, 2014; Mawdsley et al., 2009; Munang et al., 2013). There is an urgent need for reviews of the scientific evidence that supports EbA activities (Doswald et al., 2014; Munang et al., 2013). Because plants are sometimes used to support EbA, it is important to review the engineering capacity of plants to illustrate their widespread potential as a primary tool for EbA. This information can be used to more generally inform all activities where people choose to alter vegetation in the landscape (Larsen, 2015; Mahmood et al., 2014; Naudts et al., 2016; Ryan et al., 2010): urban planning, landscaping, farming, forestry, conservation, and restoration. We review the evidence that vascular plants can impact, both positively and negatively, some of the abiotic and biological stresses of climate change for co-occurring taxa (Figs. 1 and 2). Although our main focus is on the contribution of plants to desirable adaptation outcomes, plants may also contribute to detrimental impacts (e.g., providing fuel for wildfires). When plants increase damage from climate change, there is still the potential to better manage landscapes to promote their ameliorative effects (e.g., managing plants to reduce fuel loads).

As environments become more abiotically stressful (e.g., increased drought and higher temperatures), organisms tend to facilitate one another's presence and growth (Bruno et al., 2003; Mullan Crain and Bertness, 2006). Climate change is stressful to plants, in part because of local, evolutionary adaptation (or, response to natural selection) that makes changes in environmental conditions a risk to existing, evolutionarily-adapted populations (e.g., Mawdsley et al., 2009). Climate change will largely increase abiotic stress in environments, increasing aridity and heat stress. However, some environments will become cooler and wetter. Altered rainfall patterns predicted with climate change may shift environments from arid conditions with limited competition to mild conditions where competitive interactions dominate (e.g., Suttle et al., 2007). However, regardless of the direction of environmental change, because of their function as ecosystem

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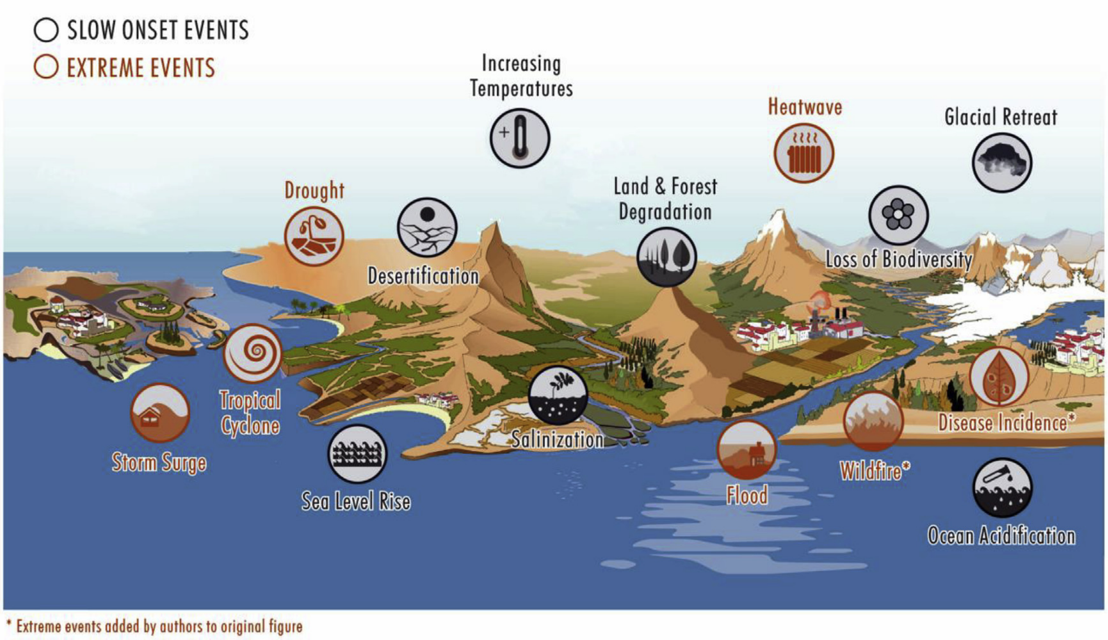

Fig. 1. Examples of potential loss and damage that can result from climate change through slow onset events or extreme weather (rapid onset) events (image used courtesy of UNFCCC; *wildfire and disease incidence added to original figure; UNFCCC, 2011). This paper focuses on how plants can alleviate effects of drought, tropical cyclones, storm surges, sea level rise, salinization, desertification, increasing temperatures, floods, heat waves, loss of biodiversity, wildfire, and disease incidence.

engineers, some plant species may slow the rate of environmental change for neighboring and dependent taxa such that they are sheltered from the extremes of direct effects of climate change (De Frenne et al., 2013; Hastings et al., 2007).

Ecosystem engineers modify the abiotic environment in such a way that the distribution, abundance, growth, or fitness of co-occurring taxa are altered. Identifying particular organisms as ecosystem engineers is a subject of heated debate because most organisms are ecosystem engineers for at least some co-occurring taxa (Mullan Crain and Bertness, 2006). Still, just as it is possible to study the physiology of organisms to the exclusion of their effects on others, examining the ways in which plants alter the environment for themselves and co-occurring taxa is a critical endeavor. Ecosystem engineers fundamentally affect how communities and ecosystems experience climate change and are an important tool that humans can use to further alleviate climate change effects. It is highly likely that non-plant taxa also alleviate effects of climate change for some co-occurring organisms, and we do not mean to imply otherwise by solely examining the role of plants in this paper. We highlight the relevance of plant ecosystem engineers to climate change by first demonstrating the relationships (both positive and negative) between vegetation and climate change effects and then by illustrating how careful selection of plants might counteract (but not remove) almost every impact of climate change (Fig. 1).

2. The role of plants in alleviating climate change-driven ecosystem shifts

2.1. Defining slow and rapid onset events

Effects of climate change can occur at different temporal scales (i.e., slow or rapid onset climate change events; Fig. 1) and some effects are proximately driven by vegetation patterns. For example, *wildfire* (rapid onset) depends on fuel availability while *desertification* (slow onset) is driven by loss of plant cover. Ecologically-speaking, the difference between rapid onset and slow onset events may be academic—the effects (or, damage) from both are conditioned by past events, and ecological systems are usually comprised of multiple linked processes occurring at different temporal and spatial scales (Galaz et al., 2011). Slow and rapid onset climate events can interact to bring natural communities and ecosystems past thresholds where intervention or environmental reversals will fail to return these communities or ecosystems to their former states. From management, insurance, and policy perspectives, slow onset and rapid onset events differ in that rapid onset events require similarly rapid responses, which is a traditional approach to disaster management and mitigation, with preparation (pre-event) and response (post-event) activities clearly delineated (Cutter et al., 2008). Rapid onset events, because they are sudden and catastrophic do not lend themselves well to models and predictions and therefore policy tends to be reactive, rather than proactive (Galaz et al., 2011). Slow onset events allow for ongoing adaptation within the developing impact (Cutter et al., 2008). Examples of EbA that we include below involve crisis-oriented loss management for rapid onset events (such as interplanting to reduce crop damage from heat waves; Fig. 5) and reorganized ecological systems under slow onset new conditions (e.g., Galaz et al., 2011) such as salt marsh accretion in response to sea level rise (see below and Fig. 3).

2.2. How plants can alleviate climate change impacts also depends on their response to the environment

The reciprocal nature of how plants are both influenced by and influence their environment is important for understanding the extent of and limits to the role of plants in alleviating climate change effects. Plants respond directly to changes in environmental conditions (which can vary from daily to millennial time-scales) and respond indirectly to changes in species interactions (e.g., competition; Laughlin, 2014; Suding et al., 2008). Plant responses (i.e., environmental filtering) will select for species and genotypes (i.e., genetically unique individuals within a species) with high performance and fitness under current conditions (Funk et al., 2008; Laughlin, 2014; Suding et al., 2008). Ultimately, these processes feed back as plants respond to their environment, resulting in a changed plant community composition (i.e.,

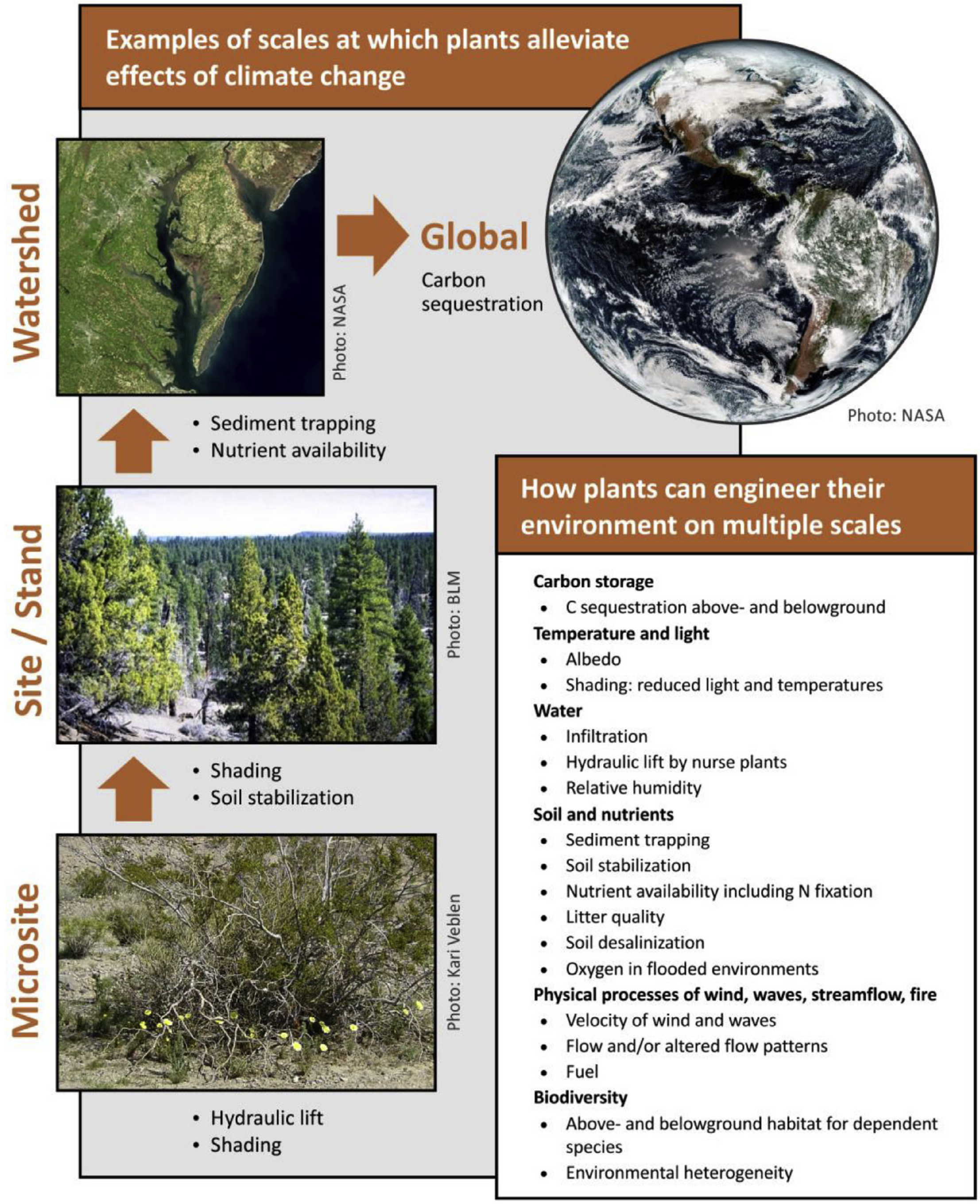

Fig. 2. Plants can engineer their environment, including in ways that are important for alleviating the effects of climate change. The spatial scales at which these engineering effects occur vary from the (micro)site to regional/landscape scales.

altered presence and relative abundance of species), which in turn results in an altered environment (Suding et al., 2008). In fact, intentional choices of particular genotype or species assemblages (that will survive under current and projected future conditions) is one way that we can use plants to alleviate the impacts of climate change (i.e., to achieve desired functional outcomes; Kettenring et al., 2014; Laughlin, 2014). Reciprocity is one reason a variety of professionals should be consulted when planning plantings (see below and Fig. 5).

2.3. Plants alleviate the impact of rapid onset effects

Plants counteract the effects of hydroclimatic *drought* ("abnormal precipitation shortfalls"; Kallis, 2008) in the same way they counter desertification (*see below*; Figs. 1 and 2). Increased plant cover counteracts drought by increasing water infiltration via root penetration of the soil surface (reducing runoff-based erosion and increasing water availability to plants), reducing wind velocity (i.e., wind-based erosion), reducing soil water loss through shading, enhancing the recycling of water vapor, and promoting greater productivity at higher trophic levels by providing food and habitat (Fig. 2) (De Frenne et al., 2013; e.g., Mawdsley et al., 2009; Ryan et al., 2010; Verchot et al., 2007). Nurse plants can increase water availability not only through shading and increased infiltration (Cavieres et al., 2002) but also by hydraulic lift (where plant roots are a physical conduit, equalizing water potential gradients among roots and deep and shallow soil fractions; Caldwell et al., 1998). In addition to the shading provided by living plant

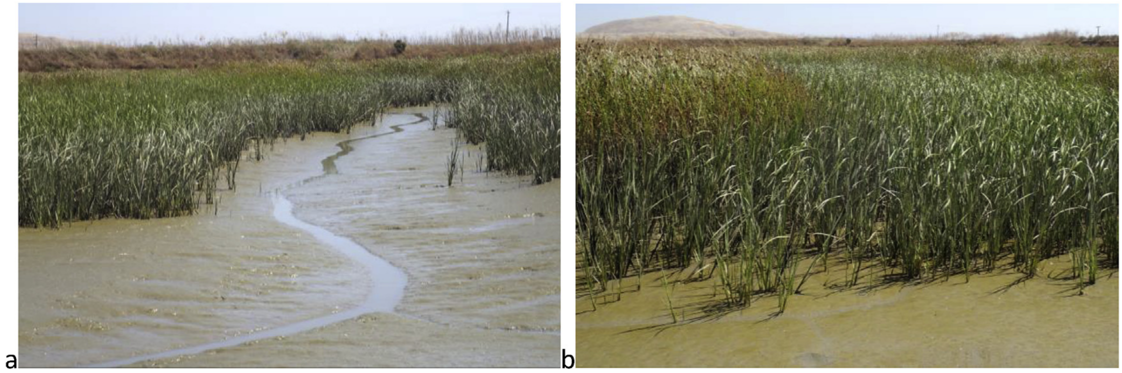

Fig. 3. (a) Native *Spartina foliosa* (California or Pacific cordgrass) in San Pablo Bay National Wildlife Refuge, California, USA and **(b)** *S. foliosa* mixed with *Bolboschoenus maritimus* spp. *paludosus* (salt marsh bulrush) (images by Brenda J. Grewell). Conservation and restoration of native coastal wetland plants are key for combatting sea level rise. Such plants can form substantial organic soil horizons and trap organic and mineral matter for accretion to keep pace with sea level rise.

biomass, litter accumulation also changes soil moisture levels; plants that accumulate more litter, or that produce litter that is recalcitrant to decomposition, increase soil moisture levels (Deutsch et al., 2010). Also, dense forest canopies result in higher humidity levels in the understory, which can buffer drought effects (De Frenne et al., 2013; Ryan et al., 2010). Land-atmosphere feedbacks, driven by vegetation and topography, can determine precipitation amounts and frequencies (Mahmood et al., 2014). Without changes in plant community composition, plants may only counteract absolute effects of drought events (water availability will still be reduced) but when communities change (or are changed through climate adaptation activities) to produce more cover or litter, the relative impact of drought may also be reduced. Intentional plantings to reduce the environmental impact of drought have focused on the planting of drought tolerant plant genotypes and afforestation (Chong, 2014; Colls et al., 2009; Henry et al., 2012). Economic impacts of drought have been reduced by increased diversity of crops and other agricultural products (Chong, 2014; Colls et al., 2009).

On the other end of hydrologic extremes, plants also play a critical role in ameliorating the impacts of *floods*, with plant mechanisms (largely through increased infiltration) operating particularly at the (micro)site scale (Figs. 1 and 2). The positive plant effects, though, can scale up to implications for flooding at the watershed scale and beyond. For instance, flood frequency is strongly and negatively correlated with percent of remaining forest (Bradshaw et al., 2007). Plants can slow the movement of water (particularly well-documented in rivers; Gurnell, 2014), and larger, more woody, and more stiff species have greater influences (O'Hare et al., 2016). Also, plants reduce the impacts of waves and wind through the interaction of plant flexibility, stem density, and height with wave period and height—with repercussions for the effects of *storm surges* and *tropical cyclones/typhoons* (Duarte et al., 2013; Hu et al., 2015; Möller et al., 2014; Rupprecht et al., 2017). These plant effects are species-specific, thereby the dominant vegetation type can determine natural coastal resilience to catastrophe (Rupprecht et al., 2017). The benefits of particular species may also vary by coastal depth profile and the configuration of coastal reefs (Colls et al., 2009). EbA to reduce storm surge damage has been to plant mangrove forests in many tsunami-prone areas on the Pacific and Indian Oceans (Fig. 5),

Fig. 4. (a) Seedling plug, (b) whole plant transfer (image courtesy of David England), and (c) hydroseeding of native wetland bulrushes as example approaches for active revegetation in the context of EbA.

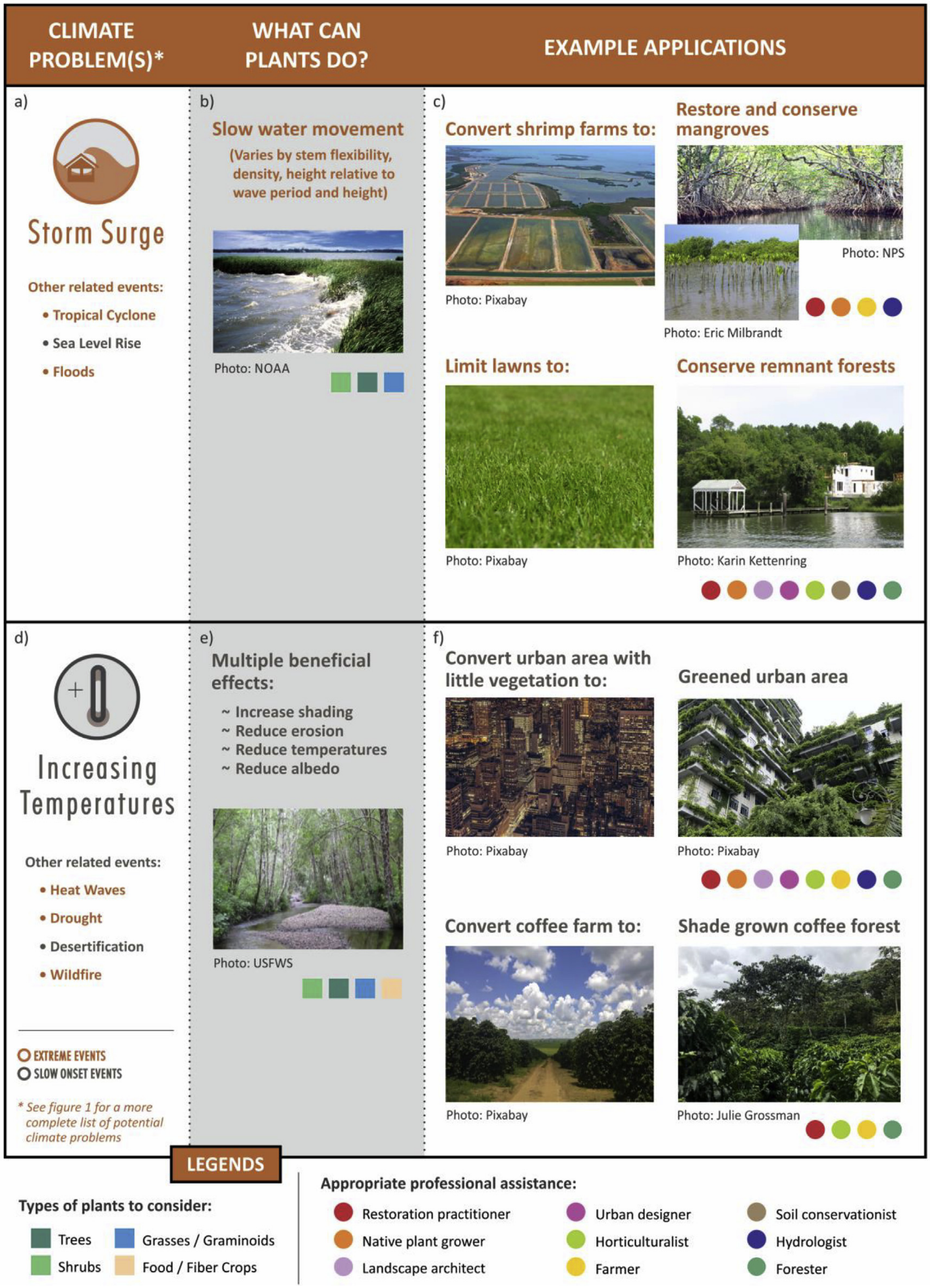

Fig. 5. Decision making framework for utilizing plants strategically for alleviating effects of climate change.

and many communities have chosen afforestation approaches for flood control (Chong, 2014; Colls et al., 2009; Lafortezza et al., 2017).

Wildfire is a physical process dependent on fuel availability and ignition, both of which are affected positively and negatively by plants (Bond and Keeley, 2005). Specifically, plant biomass directly influences fuel loads, and wildfire intensity can be exacerbated by secondary compounds that increase flammability. Landscape homogeneity driven by uniformity of plant cover (weeds, agricultural abandonment, fire suppression) increases size of wildfires (e.g., Brooks et al., 2004). Conversely, land management with tools that may include fire promoting heterogeneity in fuel loads can reduce wildfire damage (Butz, 2009). Fire can increase biodiversity and counteract desertification or, on balance, accelerate climate change by producing greenhouse gases. Therefore, wildfire can have a variety of benefits and drawbacks in the face of climate change. In the long-term, desertification caused by climate change will decrease fuel loads (Doblas-Miranda et al., 2015).

However, increasing wildfires may have feedback effects on landscapes by changing species dominance to those that accumulate greater fuel loads (e.g., Bond and Keeley, 2005). The combination of more frequent drought and earlier, higher temperatures increases wildfire impact because of greater early-season fuel availability (drier plant biomass early in the year) and increased ignition frequency (less ignition energy is required when fuels are drier). In addition, in some ecosystems, invasive species add to fuel availability (Brooks et al., 2004). In other ecosystems, higher human population densities (an indirect climate change driver) increase ignition frequencies (Romero-Calcerrada et al., 2008). Fire resistant species and genotypes can be planted to reduce wildfire damage, and strip-planted perennial grasses or forbs that remain green during the fire season will slow or contain some fires (Pellant, 1990). Fire may be necessary to maintain ecosystem function in fire-prone systems, promoting biodiversity and counteracting desertification (e.g., Butz, 2009; Carlsen et al., 2017). Climate change has already altered vegetation management via fire, where managers are less likely to use fire as a management tool (Butz, 2009); strategic plant choices that confer fewer wildfire risks may allow managed fire to be returned to some landscapes. At scales larger than local management, however, wildfires may increase the rate of climate change and associated effects via carbon emissions through combustion, plant mortality leading to reduced carbon sequestration, and reduced plant cover leading to desertification and changes to albedo.

Locally, plants have the ability to buffer dependent species from directly experiencing extreme temperatures such as *heat waves* (Figs. 1 and 2), which are expected to increase in severity and frequency with climate change. In forests, shading by overstory trees can mediate warming temperatures for understory species (De Frenne et al., 2013). The architecture of vegetation is used in agroecosystems and urban areas for wind protection and cooling (Fig. 5) (Lafortezza et al., 2017; Ryan et al., 2010). For example, overstory shade trees are being interplanted into cacao farms in West Africa (Schroth et al., 2016) to alleviate the high temperatures cacao trees are already experiencing due to climate change. Similar benefits of plants for cooling can occur in aquatic systems. Specifically, because vegetation reduces erosion, plants indirectly cool water because muddy water warms faster. Plants also directly cool water via shading, with as much as a 10 °C cooling effect, which can keep streams within invertebrate and cold/cool water fish thermal tolerances (e.g., Pörtner and Knust, 2007). Urban greening, planting street-level trees, green roofs, and greening walls with climbing plants reduces albedo and can cool urban landscapes (Lafortezza et al., 2017; Taha, 1997). In these cases, plants directly and indirectly decrease heat wave impacts.

Plants can play a positive or a negative role in *disease* vector population dynamics that are driven by climate change (Figs. 1 and 2). Some diseases are expected to increase in incidence and severity as killing low temperatures for disease vectors become less frequent due to climate warming. Water-borne diseases are expected to increase as water temperatures rise, however plants can cool water temperatures (*see above*). Invasive plants may cause particularly rapid changes in population dynamics of diseases. Giant reed (*Arundo donax*) infestations reduce soil temperatures and promote survival of the tick that transmits bovine babesiosis (Racelis et al., 2012). Plant invasions can also increase food resources for disease vectors, for example invasive plant seeds provide food for high population densities of deer mice that carry the hanta virus (Pearson and Fletcher, 2008). Therefore, plants' ability to ameliorate temperatures can have direct effects on disease incidence or, plants may bolster populations of important hosts and increase disease for other taxa indirectly. In a simpler example contained within a single trophic group, milder winter temperatures in some areas have caused increased disease and pest incidence in crops. In these cases, resistant varieties are being developed and planted, intercropping techniques have been adopted, and grazing is utilized for greater disease control (Colls et al., 2009).

2.4. Plants alleviate the impact of slow onset effects

Plants alleviate long-term *temperature increases* for neighbors (Figs. 1 and 2) in much the same way they reduce extreme temperatures (*described above*). Global temperatures will rise as much as 4 °C by 2100 due to climate change (Pachauri et al., 2014). While plants can act to cool absolute temperatures experienced by dependent taxa, relative temperature increases cannot be avoided without increasing shade or otherwise altering albedo (Li et al., 2014; Mahmood et al., 2014; Morris et al., 2016). Plants therefore have the capacity to reduce increasing temperature impacts, and intentional choices to plant more trees, increasing tree cover to reduce temperature increases, are part of EbA in urban planning (Lafortezza et al., 2017; Li et al., 2014; Rosenfeld et al., 1995).

Plants affect *desertification* in similar ways to reducing drought effects (Figs. 1 and 2). Desertification is a decrease in biological productivity that can be driven by decreased rainfall, disturbance, or land use change (Doblas-Miranda et al., 2015). Plants counter desertification by reducing erosion, increasing water infiltration via root penetration of the soil surface, and reducing soil water loss through shading (drought, *see above*). Desertification occurs when plant cover decreases, evaporative soil water loss and erosion are high, leading to further decrease in plant cover. Management to increase plant cover can decrease desertification impacts. Desertification has been decreased in some instances by planting water use efficient genotypes (Henry et al., 2012), or by adding plant propagules to the system (i.e., assisted colonization, King and Hobbs, 2006).

Wetlands have been shown to accrete (grow vertically through accumulation of sediment and organic matter) at a pace equal with historic *sea level rise* (Figs. 1 and 2) due to stabilizing ecogeomorphic feedbacks that include plant-driven surface and subsurface processes (Fig. 3; Gedan et al., 2011; Kirwan and Megonigal, 2013). Sea level rise, coupled with other anthropogenic impacts of eutrophication and sediment deprivation, can result in partial and total loss of salt marshes (Gedan et al., 2011; Kirwan and Megonigal, 2013) but models suggest that many salt marsh plants have the ability to sufficiently accrete with projected sea level rise (Kirwan et al., 2016). Salt marsh accretion results from subsurface processes related to root growth and organic accretion (Kirwan et al., 2016). Furthermore, litter production at the surface adds to marsh elevation. Litter also creates “roughness” that traps incoming sedimentary and organic particles and reduces their resuspension (Kirwan et al., 2016). The engineering ability of this litter can differ widely by species due to variation between species in quantity of litter as well as morphology and longevity of litter that is driven by its chemical composition (e.g., lignin). In the United Kingdom, managers have deliberately compromised seawalls and allowed natural recolonization to restore salt marshes, reducing flood risk and wave damage resulting from sea level rise (Colls et al., 2009).

Biodiversity typically benefits the provisioning of ecosystem functions and services that counteract degradation (Cardinale et al., 2012). With climate change, there will be a *loss of biodiversity* as species go extinct when their niches disappear, or when they cannot migrate or evolve rapidly enough to meet the challenges of environmental change. Plant conservation and restoration activities such as assisted migration not only increase the biodiversity of plant communities, but also the diversity of other trophic levels via habitat provisioning (as in Mawdsley et al., 2009). Restoration based on revegetation often relies on the premise that creating habitat through plant diversity concomitantly brings diversity of higher tropic levels to a location, which is sometimes but not always the case (Hilderbrand et al., 2005). Therefore, more sophisticated information is required regarding the habitat provisioning aspect of plant ecosystem engineering and in some instances, revegetation may be insufficient when used as the sole tool in habitat restoration.

Salinization is an accumulation of salt in surface layers of soil (Figs. 1 and 2), caused by deposition alone (including from sea level

rise) or in combination with lowered plant cover and diversity, from processes such as desertification. Under extreme conditions (Daigh and Klaustermeier, 2016), or when deposition is a regular occurrence (e.g., Parker et al., 2011), plants cannot counteract salinization without additional intensive management of soil chemistry and hydrology. However, salinization can be reduced and in some cases reversed by establishing a diversity of rooting depths in the plant community and increasing plant cover which decreases soil evaporation, thereby driving salts to depth via physical processes mediated by plants (Byers et al., 2006).

3. Restoration as an example of purposeful plant selection for climate adaptation

Ecological climate change adaptation activities often involve active management and manipulation of vegetation. Purposeful plant selection should be applied to urban planning, farming, forestry, conservation, habitat management, and restoration as an efficient, sustainable solution for alleviating climate change impacts. Here we focus on ecological restoration as an example of how this strategy could be implemented. As the enterprise of restoration grows globally, revegetation activities are positioned exceptionally well to incorporate climate adaptation in practice. Not only is it critical to consider climate change in designing and implementing restoration because non-equilibrium ecosystems, or sites where plant communities are reassembling after a disturbance event, respond more strongly to climate change than equilibrium ones (Kröel-Dulay et al., 2015), but also, species should be protected from extinction as their ecological niche either moves faster than the species' capacity for migration or its niche disappears altogether (Lanza and Stone, 2016; Roloff et al., 2009). Restoration includes assisted migration (bringing genotypes or propagules to the site via seeding or transplanting, Fig. 4), habitat construction (such as terraforming and watershed restoration), and preserving evolutionary potential (bolstering genetic diversity and maintaining or increasing gene flow). Revegetation, or assisted migration of plants, reduces desertification (King and Hobbs, 2006), mitigates wildfire (Pellant, 1990), and reduces the extreme temperatures of urban heat islands (Rosenfeld et al., 1995). More sophisticated and specific application of plants as ecosystem engineers in reducing costs and increasing restoration success is increasingly recognized (Borsje et al., 2011; Byers et al., 2006; Gómez-Aparicio, 2009). The use of halophytes in desalinization is an example (Byers et al., 2006). To increase these applications, there are many areas where research needs are still great, such as in the role of plants in biotic resistance (i.e., limiting the invasion of undesirable species), and benefits could be restricted to particular species or genotypes. The cost, time, and effort of determining their identity and the extent to which ecosystem engineers provide benefits to dependent species (e.g., Mullan Crain and Bertness, 2006) is an obstacle to sophisticated application of ecosystem engineers within restoration as part of EbA.

4. Decision process for strategic choice of plants for climate adaptation

As outlined above, there are myriad ways that plants can alleviate the effects of climate change. However, how might a local community or land manager actually manipulate vegetation to achieve desired goals and outcomes? Here we provide two specific examples for climate problems of storm surge (Fig. 5a) and increasing temperatures (Fig. 5d), and outline a decision making framework for others to follow. In the example of storm surge, the first step is to recognize what plants can (and cannot do) to assist with this issue. In this case, as described above, plants are integral to slowing water movement, but the ability of different plants to affect water movements varies by their stem flexibility, density, and height relative to wave period and height (Fig. 5b). Therefore, plant choice is extremely important, and the species used would be chosen from the most applicable functional groups (native trees, shrubs, grasses/graminoids, and food/fiber crops; Fig. 5) and appropriate for the climate and site conditions. In coastal environments, storm surge would in most cases be best reduced by wetland trees, shrubs, and graminoids adapted to saline/brackish conditions (Fig. 5b). Specific actions to address storm surge would be to prioritize conservation of existing mangroves, and in the case where these habitats have been lost to shrimp farms, for example, restoration of mangroves through active replanting is essential (Fig. 5c). Such efforts would require assistance from diverse professionals including restoration practitioners, native plant growers, hydrologists, and farmers (Fig. 5c). In other locations where suburban development is very close to shorelines, an emphasis on conserving existing forests (e.g., in Chesapeake Bay subestuaries as shown in Fig. 5c) minimizes the impacts of storm surge (Sutton-Grier et al., 2018). Nature-based infrastructure such as native forests, or even tree plantings, provide more climate-related positive functions than planting lawns (Lafortezza et al., 2017).

In the case of increasing temperatures, plants provide multiple benefits through increased shading and reductions to erosion, albedo, and overall temperatures (Fig. 5e). These effects transcend ecosystem type thus we can see these plant benefits in diverse locales such as in dense urban areas and in shade grown coffee forests. For instance, we can greatly reduce temperatures in urban areas traditionally dominated by built infrastructure and little vegetation to an urban oasis where vegetation is present throughout, on top of, by the side of, buildings (Fig. 5f), particularly through the use of trees and shrubs, and perhaps grasses/graminoids. A wide array of professionals would need to be enlisted in such efforts from urban designers to landscape architects and horticulturalists (Fig. 5f). In the shade grown coffee example, an industrialized coffee farm often has no overstory whereas shade grown coffee forests are replete with forest canopy trees (Fig. 5f). Guiding such an effort would require the assistance of foresters, farmers, horticulturalists, and restoration practitioners (Fig. 5f). Ultimately, the integration of plants into how we manage our landscapes can be harnessed in diverse and imaginative ways to reduce the impacts of climate change.

5. Conclusions and applications

Plants are incredibly effective at altering environmental conditions including alleviating the negative effects of climate change. As such, plants are an efficient approach to EbA. Developing and more at-risk countries often turn to EbA because it is relatively inexpensive and can alleviate damage imposed by climate change. The "soft approach" of EbA that includes plants as ecosystem engineers is more sustainable and inexpensive than engineering solutions (Chong, 2014; Watts et al., 2011). Hard engineering approaches such as seawalls, riprap revetments, and bulkhead have been used to deal with rising sea level, storm surges, and hurricanes (Duarte et al., 2013; Feagin et al., 2015; Gittman et al., 2015). While these approaches are useful under some circumstances, they can be extremely expensive, have limited life spans, and cannot change in response to shifting climate change impacts (Duarte et al., 2013; Feagin et al., 2015). In contrast, strategic plant choices for climate change adaptation have broader benefits because plant-based biodiversity supports a myriad of ecosystem functions and services (Cardinale et al., 2012). While the natural processes of evolution and community assembly may need interventions to keep pace with the rate of climate change (e.g., Shaw and Etterson, 2012), ecosystems possess an intrinsic capacity to respond to environmental change (Duarte et al., 2013; Feagin et al., 2015). Climate adaptations are designed to alleviate specific and local risks engendered by climate change, and in this paper we have provided examples of how plants may alleviate (but ultimately not remove) most of these risks. Strategic plant choice should be incorporated into the myriad ways in which we manipulate vegetation in our environment (e.g., Mahmood et al., 2014; Naudts et al., 2016; Ryan et al., 2010), not just EbA activities. By providing a central reference for

the ability of plants to counteract damage from climate change, we hope to focus farming, forestry, urban planning, conservation, and restoration activities on the powerful and sustainable capacities of plants to modify their environments.

Conflicts of interest

None.

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